L1 Adaptive Control for Missile Longitudinal Dynamic using MATLAB/Simulink

by - Munadi

International Journal of Mechanical Engineering and Technology (IJMET)
Volume 9, Issue 10, October 2018, pp. 1346–1355, Article ID: IJMET_09_10_138
Available online at http://www.iaeme.com/ijmet/issues.asp?JType=IJMET&VType=9&IType=10
ISSN Print: 0976-6340 and ISSN Online: 0976-6359

L_1 ADAPTIVE CONTROL FOR MISSILE LONGITUDINAL DYNAMIC USING MATLAB/SIMULINK

M. Munadi
Department of Mechanical Engineering, Diponegoro University, Semarang, Indonesia

Mochammad Ariyanto
Department of Mechanical Engineering, Diponegoro University, Semarang, Indonesia

Yoga D. Setiawan
Department of Mechanical Engineering, Diponegoro University, Semarang, Indonesia

M. Amir Abdullah
Garuda Maintenance Facility AeroAsia, Soekarno Hatta International Airport, Cengkareng, Indonesia

Ahmad Hasan Fauzi
Garuda Maintenance Facility AeroAsia, Soekarno Hatta International Airport, Cengkareng, Indonesia

Muhammad Nanda Setiawan
Department of Physic Energy Engineering, Surya University, Tangerang, Indonesia

ABSTRACT

The control technology grows rapidly at the present, especially in the aeronautics field. This research deals with how the adaptive control technology solve the problems related to a usability, performance, robustness, and the time adaptability in the uncertainty conditions issues. The dynamic characteristics of the missile are modelled in Simulink which is limited only for 3 degrees of freedom in longitudinal section. The parameter values of missile will be inserted into MATLAB in order to obtain the dynamic equation in state space or transfer function at a certain operating point. The transient behaviour of the system will be monitored as the disturbance applied to the system. In order to analyse the response of the system, the L_1 adaptive control with PI controller is applied. This method can able to guarantee the better stability using Lyapunov analysis and abilities to perform the adaptation process immediately without losing robustness by adding a Low Pass Filter (LPF) on the algorithm architecture. The result of L_1 adaptive control performance will be compared to some other control *methods such as Proportional-Integral (PI) control and Model Reference Adaptive Control (MRAC).*

Keyword head: L_1 adaptive control, Lyapunov, Missile longitudinal dynamic, MRAC.

Cite this Article M. Munadi, Mochammad Ariyanto, Yoga D. Setiawan, M. Amir Abdullah, Ahmad Hasan Fauzi and Muhammad Nanda Setiawan, L1 Adaptive Control for Missile Longitudinal Dynamic Using Matlab/Simulink, *International Journal of Mechanical Engineering and Technology*, **9**(10), 2018, pp. (1346)-(1355).
http://www.iaeme.com/IJMET/issues.asp?JTypeIJMETT&VType=9&IType=10

1. INTRODUCTION

Adaptive control has been widely applied in various fields of control systems. This is because the adaptive control has a better performance to cope the disturbance compared to other methods, i.e. PID controller, Fuzzy logic, etc. Application of adaptive control related to robotic fields has been done by Munadi, where it gives better performance against a change of parameters on a robot arm and DC motor [1, 2]. Development of adaptive control which is described by Astrom [3], has experienced rapid development in which the control algorithms have been able to guarantee robustness with rapid adaptation process. This type of adaptive control is the L_1 adaptive control [4] which is the development of MRAC [5]. Applications of L_1 adaptive control proper with aeronautics field due to its better stability performance to handle uncertainty conditions of the dynamic disturbances [6-14].

This research is conducted to modify the design of the L_1 adaptive control using baseline augmentation [7, 8]. The algorithm will be modified by adding the PI controller in an adaptive system which consists of MRAC and L_1 adaptive control. The purpose of this controller is to more easily design the transient response with less of oscillation as well as being able to quell the disturbance more quickly. The study also proved that the L_1 adaptive control is much better if compared to the MRAC [5, 15]. A plant which is used as a system is the vertical acceleration of the longitudinal motion of the missile. This conditions describe the nonlinear behaviour of the dynamics motion of the missile, so L_1 adaptive control is suitable to apply in order to deal with this condition.

2. MISSILE LONGITUDINAL DYNAMIC

The plant is analyzed only on longitudinal dimension to obtain a simple 3 degrees of freedom model, i.e. horizontal, vertical, and pitch [16,17]. The longitudinal missile equation of motion are shown in Eqs. (1).

$$\sum \Delta F_x = m(\dot{u} + wQ)\ ;\ \sum \Delta F_z = m(\dot{w} - uQ)\ ;\ \sum \Delta M = \dot{Q} I_y \tag{1}$$

Eqs. (1) consists of axial force (F_X), normal force (F_Z) and pitch moment (M). The forces and moment are obtained from acceleration and linear velocity of the missile ($\dot{u}, \dot{w}, u, v$) as well as the acceleration and angular velocity ($\dot{Q}, Q$) with the inertia moment (I_y). The forces and moments acting on missile are caused by aerodynamics effect describeb in Eqs. (2).

$$F_X = QSC_x(M, \alpha, \delta e); F_Z = QSC_z(M, \alpha, \delta e); M = QSdC_m(M, \alpha, \delta_e, q) \tag{2}$$

Two forces and a moment working on longitudinal movement of the missile contains coefficients of aerodynamic as described on the following Eqs. (3) [18]. The values of aerodynamic coefficients and parameters are obtained from references that study about experimental test of missile [19, 20], and the values are shown in the Table 1. The values of all aerodynamic coefficients are related to the Mach number and angle of attack of the missile as shown in Figure 1.

$$C_x = (C_x(M,\alpha) + C_{x\delta e}\delta_e)\,; \qquad C_z = (C_z(M,\alpha) + C_{z\delta e}\delta_e)\,;$$
$$C_m = \left(C_m(M,\alpha) + C_{m\delta_e}\delta_e + C_{mq}q\right) \tag{3}$$

Table 1 The missile parameters.

No	Parameter	Value	Unit
1	Mass m	85	K_g
2	Moment of inertia I_{yy}	215	K_g/m^2
3	Gravitational acceleration g	9.81	m/s^2
4	Missile diameter d	0.127	m
5	Reference area S	0.0507	m^2
6	Linear velocity v_0	600	m/s
7	Linear velocity w_0	0	m/s
8	Angular velocity q_0	0	rad/s
9	height h_0	3000	m
10	Absolut temperature T_0	288.16	K
11	Density ρ_0	1.2250	K_g/m^3
12	Static pressure P_0	101325	N/m^2
13	Altitude	11000	m
14	Characteristic gas constant	287.26	$J/K_g/K$
15	Damping ratio ζ	0.7	-
16	Natural frequency ω_n	150	$1/s$
17	Elevator effectiveness of axial force $C_{x\delta e}$	0	-
18	Elevator effectiveness of normal force $C_{z\delta e}$	-1.9481	-
19	Elevator effectiveness of moment $C_{m\delta e}$	-11.9029	-
20	Moment coefficient due to pitch rate C_{mq}	-1.1790	-

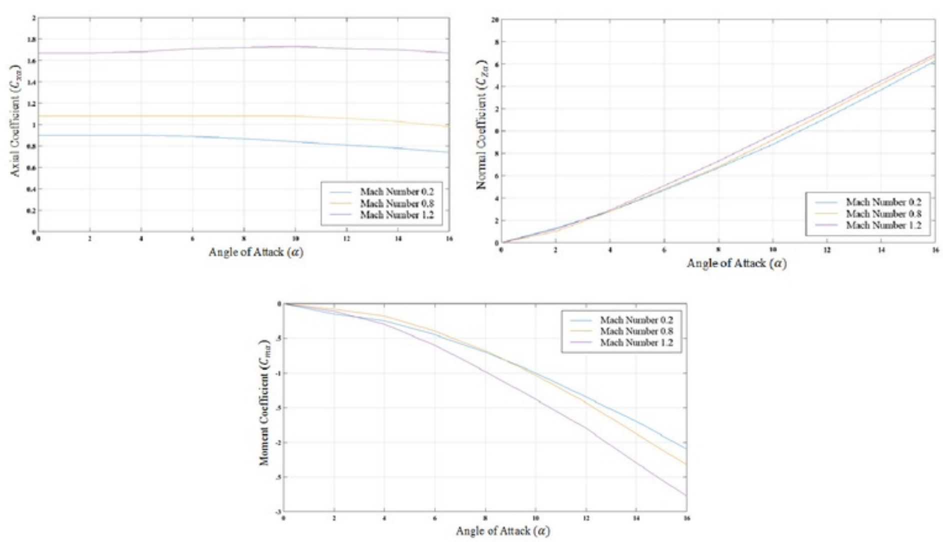

Figure 1. Aerodynamic coefficients (Axial, Normal, and Moment) at several constant Mach Numbers with function of the angle of attack (α)

All obtained value of the parameters and aerodynamic coefficient are then substituted into the previously mentioned equations and compiled into a correlating system as shown in Figure 2.

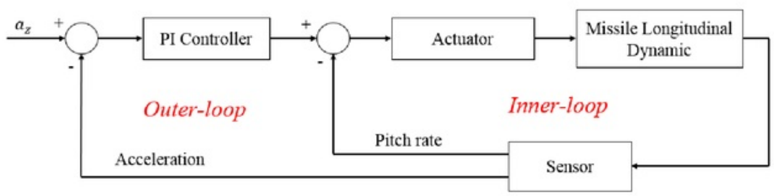

Figure 2. The diagram block scheme of control system in longitudinal missile dynamic.

The system shown in Figure 2 is a non-linear system and need to be linearized on a specified operating point where the missile works. The pitch and vertical acceleration are linearized to produce a steady value and expressed in the form of transfer function in following Eqs. (4) and (5).

$$\frac{\dot{\theta}(s)}{\delta(s)} = \frac{-57.57s-396.9}{s^2+15.4s+80.74} \tag{4}$$

$$\frac{a_z(s)}{\delta(s)} = \frac{-160.5s^2-1388s+238200}{s^2+15.4s+80.74} \tag{5}$$

To design an adaptive control of the controlled parameter (vertical acceleration in this case) Eqs. (5) need to be altered into state space form as shown in Eqs. (6) and (7).

$$\dot{x}(t) = A_m x(t) + bu(t) \;\; y(t) = cx(t) + du(t) \tag{6}$$

$$A_m = \begin{bmatrix} -15.4 & -80.74 \\ 1 & 0 \end{bmatrix}, b = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \; c = [1084 \quad 251200], d = [-160.5] \tag{7}$$

3. DESIGN OF PROPOSED PI CONTROLLER

In this study, the PI controller will be used as a comparator to PI-MRAC and PI-L_1 adaptive control. Figure 3 shows the design of PI controller response of missile longitudinal dynamics using the automatic tuning feature in Simulink. Vertical acceleration is defined as controlled parameter. The transient response of the system as shown in Figure 3 below, while the parameter's value of the transient conditions are shown in Table 2.

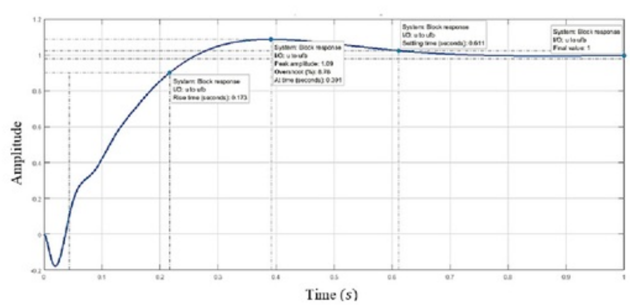

Figure 3. Response system design of PI controller with automatic tuning in Simulink.

The values of transient parameters as shown in Table 2 are the result of the PI controller as a compensator design of the vertical acceleration in longitudinal missile dynamics. The value represents the best optimization of tuning results.

Table 2 The tuning results of PI controller in Simulink.

No	Parameter	Value
1	Gain Proportional (P)	0.0012436
2	Gain Integral (I)	0.019304
3	Rise time	0.173 second
4	Settling time	0.611 second
5	Overshoot	8.78 %
6	Steady state error	0 %
7	Closed loop stability	*Stable*

4. DESIGN OF PROPOSED PI-MRAC

The control design which uses PI-MRAC is a modification of the Eqs. (6). The aim is to create an adaptive system so that the controller performance is expected to be better dealing with the disturbances. An adaptive system consists of four parts; plant, reference model, adaptation law, and control. The each of algorithms used to create an adaptive system are elaborated on sections 4.1 to 4.4 below [4].

4.1. Plants

On this system, plant is defined as vertical acceleration, which is obtained from linearized Eqs. (6) with state space matrix in Eqs. (7). In Addition, the plant is modified by adding a control input $u(t)$ and unknown parameter k_x^{T} as shown in Eqs. (8).

$$\dot{x}(t) = A_m x(t) + b\left(u(t) + k_x^{\mathrm{T}} x(t)\right) \tag{8}$$

$$y(t) = c^{\mathrm{T}} x(t) + du(t)$$

Based on the Eqs. (8), the algorithm of a plant is modified in order to neutralize the disturbance of some unknown parameters that work on the system.

4.2. Reference Model

Reference model, $\dot{x}_m(t)$ is designed to neutralize disturbance or unknown parameter. The algorithm design of the reference model is shown in Eqs. (9).

$$\dot{x}_m(t) = A_m x_m(t) + bk_g r(t) \tag{9}$$

$$y_m(t) = c^{\mathrm{T}} x_m(t) + du(t)$$

$$k_g \triangleq \frac{1}{c^{\mathrm{T}} A_m^{-1} b}$$

Based on the Eqs. (9), $r(t)$ is the input signal to the system while k_g in the Eqs. (9) aims to track the $y_m(t)$ so that the value becomes zero steady-state error.

4.3. Adaptation Law

Adaptation law as shown in Eqs. (10) is an algorithm which ensure the system is stable or converging to zero. The algorithm is obtained by using a stability analysis of Lyapunov functions as described in [1].

$$\dot{\hat{k}}_x(t) = -\Gamma x(t) e^{\mathrm{T}}(t) P b \tag{10}$$

$$A_m^{\mathrm{T}} P + P A_m = -Q \tag{11}$$

Based on the Eqs. (10), $\hat{k}_x\ (t) \in \mathbb{R}^n$ is the parameter estimation of k_x which serves to damp the disturbance from uncertain parameter. e^{T} is an error value that is obtained from $e(t) \triangleq x_m(t) - x(t)$. Gamma Γ is the value which is used to improve the process of adaptation. Matrix $P = P^{\mathrm{T}} > 0$ is obtained by using a Lyapunov function in Eqs. (11) where $Q = Q^{\mathrm{T}} > 0$ and an arbitrary matrix.

4.4. Controller

Adaptive control system as shown in Eqs. (12) is an algorithm that is used to eliminate disturbance of uncertain parameters of the plant in Eqs. (8).

$$u(t) = -\hat{k}_x^{\mathrm{T}} x(t) + k_g r(t) \tag{12}$$

The simulink diagram block of Eqs. (8)-(12) is shown in Figure 4, where the four parts of the adaptive system are connected.

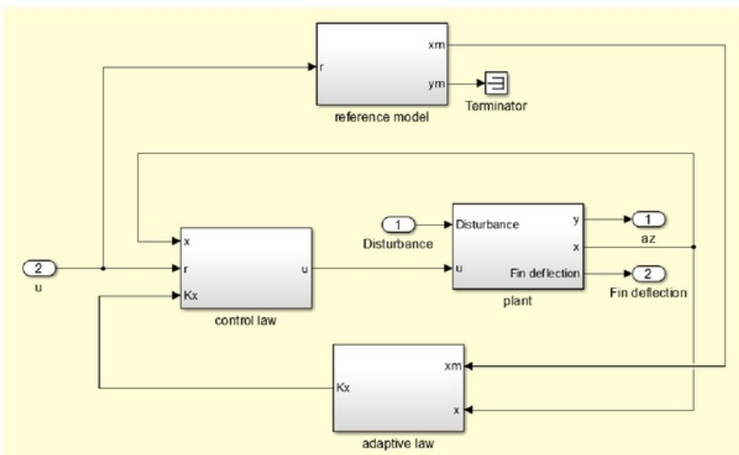

Figure 4. Simulink design of MRAC

The MRAC system design shown in Figure 4 is a plant that is able to adapt to the uncertain parameters. The next step is designing the transient response of the system by using MRAC with PI controller. It is shown in Figure 2 in order to obtain the result of response systems. The result is shown in Figure 5.

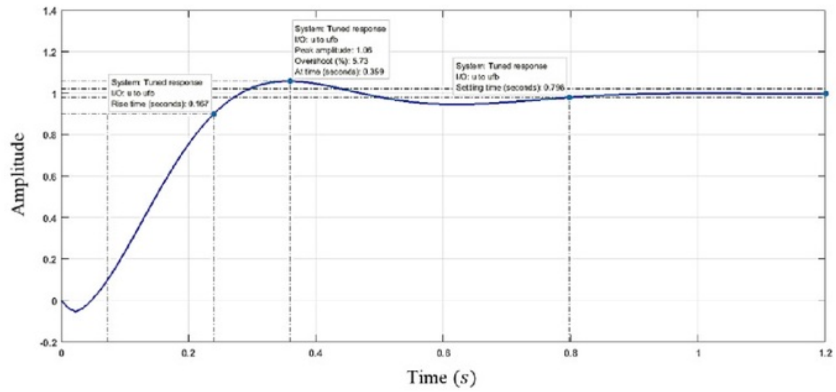

Figure 5. Design response system of PI-MRAC with automatic tuning in Simulink.

The design he design of the system response in Figure 5 is the control design in the transient phase when the the tuning result of PI-MRAC is shown in Table 3. Based on Table 3, there are improvements of transient response characteristics compared to the use the PI controller regarding rising time and overshoot.

Table 3 Tuning results of PI-MRAC in Simulink.

No	Parameter	Value
1	Gain Proportional (P)	1.1545
2	Gain Integral (I)	6.4877
3	Rise time	0.167 second
4	Settling time	0.798 second
5	Overshoot	5.798 %
6	Steady state error	0%
7	Closed loop stability	Stable

5. DESIGN OF PROPOSED PI-L1 ADAPTIVE CONTROL

L_1 adaptive control is a modification of MRAC. In L_1 adaptive controller, The MRAC algorithmic structure of the reference model section was changed to state predictor. Modifications made by Naira Hovakimyan does not ruin the dynamics of the system and has successfully overcome the disorder completely in the process of rapid adaptation due to the addition of the Low Pass Filter (LPF), $C(s)$, on the control architecture. The system used in the design of the L_1 adaptive control is shown in Eqs. (8) [4].

5.1. State Predictor

State predictor, $\dot{\hat{x}}(t)$ as shown in Eqs. (13) is a modification of the reference model in the MRAC, wherein the input signal at state predictor is obtained from the control output $u(t)$.

$$\dot{\hat{x}}(t) = A_m\hat{x}(t) + b\left(u(t) + \hat{k}_x^{\mathrm{T}}x(t)\right) \tag{13}$$

$$\hat{y}(t) = c^{\mathrm{T}}\hat{x}(t) + du(t)$$

Excess use of state predictor is an adaptive system's ability to pass through the LPF so that some disturbances with high frequency can be damped by the estimation of unknown parameters $\hat{k}_x^{\mathrm{T}}$ which is generated by the adaptation law.

5.2. Adaptation Law

Adaptation law as shown in Eqs. (14) estimates the unknown parameters $\dot{\hat{k}}_x(t)$. This value is derived from the decrease error Lyapunov functions as described in [1].

$$\dot{\hat{k}}_x(t) = -\Gamma x(t)\tilde{x}^T(t)Pb \tag{14}$$

Based on the Eqs. (14), the algorithm of the adaptation law similar to the adaptation law on MRAC in Eqs. (10), the difference is only found in $\tilde{\boldsymbol{x}}^{\boldsymbol{T}}$ which is an error generated by the difference between the state predictors in Eqs. (13) and Eqs. (8). The determination of Lyapunov matrix P is achieved by using the Lyapunov function in Eqs. (11).

5.3. Controller

Controller on L_1 adaptive control as shown in Eqs. (15) is obtained by passing the result of adaptation $\hat{k}_x^T x(s)$ and input signal $k_g r(s)$ on LPF $C(s)$ so that the high frequencies due to the accumulation of disturbance can be damped.

$$u(s) = C(s)\left(-\hat{k}_x^T x(s) + k_g r(s)\right) \tag{15}$$

There is no definite method in determining the value of LPF. The LPF value is determined by using trial and error method so that the value of LPF become as follow.

$$C(s) = \frac{35}{s+35} \tag{16}$$

The next step is implementing Eqs. (8), (13)-(15) into Simulink blocks as shown in Figure 6 where every part of the L1 adaptive control system is interconnected.

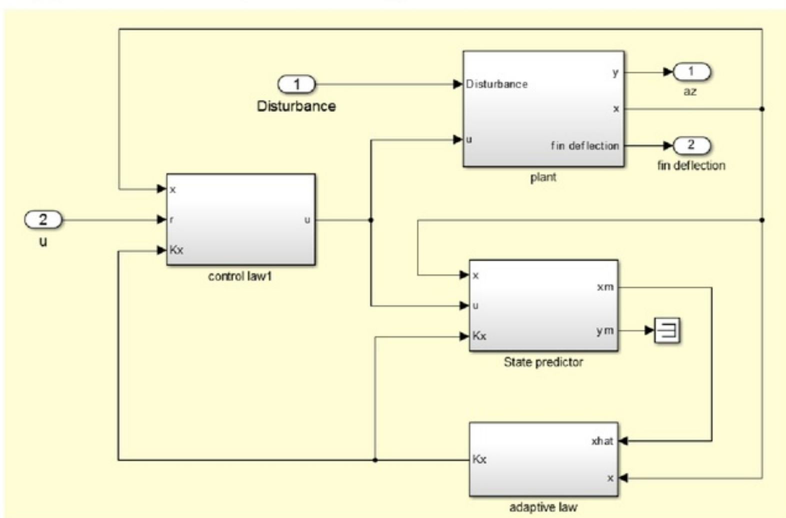

Figure 6. Simulink design of L_1 adaptive control.

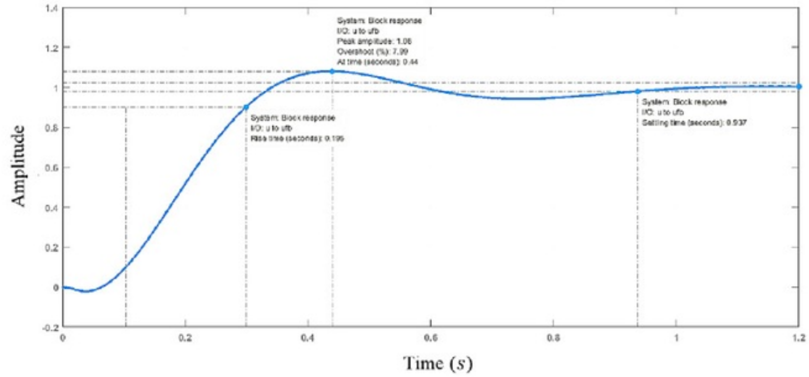

Figure 7. Response system design of PI-L_1 adapative control.

The L_1 adaptive control system design in Figure 6 is a plant controlled by using a PI controller as shown in the schematic block diagram in Figure 2. Furthermore, the design of response system is obtained by using the automatic tuning in Simulink as shown in Figure 7. The response system design in Figure 7 is a transient phase of the L_1 adaptive control system with transient characteristic parameter's values shown in Table 4.

Table 4 Tuning results of PI- L_1 adaptive in Simulink.

No	Parameter	Value
1	Gain Proportional (P)	0.91791
2	Gain Integral (I)	5.1997
3	Rise time	0.195 second
4	Settling time	0.937 second
5	Overshoot	7.99 %
6	Steady state error	0%
7	Closed loop stability	*Stable*

6. CONCLUSION

In this paper, the simulation is conducted to obtain a performance comparison of L_1 adaptive control with other control types. Addition of PI controller in the algorithm of L_1 adaptive control is capable to give the desired effect of the transient response. There are two types of simulations that have been done. The first simulation is conducted to observe the transient response of the system while the second simulation is conducted to observe the trajectory of the system when given disturbance. Based on the simulation results in the transient response, it appears that the PI-L_1 adaptive control has a stable transient response while the value of gamma increase. PI-L_1 adaptive control also has been able to reduce the severe disturbance that is received either noise or unknown parameters. It shows that the L_1 adaptive control has better performance than the PI controller and PI-MRAC.

ACKNOWLEDGEMENT

This research was financially supported by The Faculty of Engineering, Diponegoro University, Indonesia through Strategic Research Grant 2018.

REFERENCES

[1] Munadi, M., Naniwa, T. Experimental Verification of Adaptive Dominant Type Hybrid Adaptive and Learning Controller for Trajectory Tracking of Robot Manipulators. *Journal of Robotics and Mechatronics*, **25**, 2013, pp. 737-747.

[2] Munadi, M., Abdullah, M. A. Simulation of Fuzzy Logic Control for DC Servo Motor using Arduino Based on MATLAB/Simulink. Proceedings of Intelligent Autonomous Agents, Networks and Systems (INAGENTSYS), 2014 IEEE International Conference, Bandung, 2014 pp. 42 – 46.

[3] Astrom, K. J. Adaptive Control Around 1960. Proceedings of IEEE Conference on Decision, New Orleans, 1995 pp. 2784-2789.

[4] Hovakimyan, N., and Cao, C. *L_1 Adaptive Control Theory: Guaranteed Robustness with Fast Adaptation,* Philadelphia, SIAM, 2010.

[5] Butchart, L. R., & Shackcloth, B. Synthesis of Model Reference Adaptive Systems by Lyapunov's Second Method. Proceedings of *IFAC Symposium on the Theory of Self-Adaptive Control* Sistem*s*, Teddington UK, 1965 pp. 145-152.

[6] Pettersson, A., Astrom, K. J., Robertsson, A., and Johansson, R. Analysis of Linear L_1 Adaptive Control Architectures for Aerospace Applications. Proceedings of 51st IEEE Conference on Decision and Control, Maui, Hawaii, 2012.

[7] Leman, T. J. L_1 Adaptive Control Augmentation System for the X-48B Aircraft. Thesis, Chicago: University of Illionis, 2009.

[8] Pettersson, A., Astrom, K. J., Robertsson, A., and Johansson, R. Augmenting L1 Adaptive Control of Piecewise Constant Type to a Fighter Aircraft. Proceedings of AIAA Guidance, Navigation, and Control Conference, Minnesota, 2012, pp. 4757.

[9] Michini, B., and How, J. P. L_1 Adaptive Control for Indoor Autonomous Vehicles: Design Process and Flight Testing. Proceedings of AIAA Guidance, Navigation, and Control Conference, Chicago, 2009, pp. 5754.

[10] Myleus, A. L_1 Adaptive Control of a Generic Fighter Aircraft. Master Thesis, Stockholm: Stockholm University, 2013.

[11] Cao, C., and Hovakimyan, N. L_1 Adaptive Output Feedback Controller for Non-Strictly Positive Real Reference Systems with Applications to Aerospace Examples. Proceedings of AIAA Guidance, Navigation, and Control Conference, Honolulu, Hawaii, 2008, pp. 7288.

[12] Gregory, I. M., Cao, C., Xargay, E., Hovakimyan, N., and Zou, X. L_1 Adaptive Control Design for NASA AirSTAR Flight Test Vehicle. Proceedings of AIAA Guidance, Navigation, and Control Conference, Chicago, 2009, pp. 5738.

[13] Hacker, J. E. L_1 Adaptive Control of Uncertain Nonlinear Systems with Dynamic Constraints: as Applied to Commercial Aircraft Engines. Master Thesis, Connecticut: University of Connecticut, 2011.

[14] Beard, R. W., Knoebel, N. B., Cao, C., Hovakimyan, N., and Matthews, J. S. An L_1 Adaptive Pitch Controller for Miniature Air Vehicle. Proceedings of AIAA Guidance, Navigation, and Control Conference, Keystone, 2006, pp. 6777.

[15] Taylor, L. W., Adkins, E. J. Adaptive Control and the X-15. *Aircraft Flying Qualities.* Princeton: Princeton University, 1965.

[16] Siouris, G. M. Missile Guidance and Control Systems. New York: Springer, 2004.

[17] Blakelock, J. H. Automatic Control of Aircraft and Missile. New York: A Wiley-Interscience Publication (John Wiley & Sons), 1990.

[18] Loewen, H. Stability Derivatives. MicroPilot, 2013. https://www.micropilot.com/pdf/stability-derivatives.pdf

[19] Wee, H. C. *Aerodynamic Analysis of a Canard Missile using ANSYS-CFX.* Postgraduate Thesis, California: Naval Postgraduate School, 2011.

[20] Cavcar, M. The International Standard Atmosphere (ISA). Turkey: Anadolu University, 2006.

L1 Adaptive Control for Missile Longitudinal Dynamic using MATLAB/Simulink

ORIGINALITY REPORT

1%	1%	1%	1%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	www.e3s-conferences.org Internet Source	1%
2	Penne, R.. "Moves on Pseudoline Diagrams", European Journal of Combinatorics, 199608 Publication	<1%
3	Submitted to University of Bristol Student Paper	<1%
4	Bing Hua, Lin Chen, Yunhua Wu, Zhiming Chen. "A study of PID and L1 adaptive control for automatic balancing of a spacecraft three-axis simulator", International Journal of Intelligent Computing and Cybernetics, 2018 Publication	<1%

Exclude quotes	Off	Exclude matches	Off
Exclude bibliography	Off		

L1 Adaptive Control for Missile Longitudinal Dynamic using MATLAB/Simulink

GRADEMARK REPORT

FINAL GRADE

/0

GENERAL COMMENTS

Instructor

PAGE 1

PAGE 2

PAGE 3

PAGE 4

PAGE 5

PAGE 6

PAGE 7

PAGE 8

PAGE 9

PAGE 10